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Tunneling spectroscopy in CoFeB/MgO/CoFeB magnetic tunnel junctions

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The d^2V/dI^2-V measurements were used to investigate the tunneling mechanism in CoFeB/MgO/CoFeB magnetic tunnel junctions (MTJs), which showed a giant tunnel magnetoresistance ratio up to 200% at room temperature. The d^2V/dI^2-V spectra of CoFeB/MgO/CoFeB junctions resemble those of single-crystal Fe(001)/MgO(001)/Fe(001) MTJs. Broad peaks appeared around ±600 mV in spectra for antiparallel magnetic configurations. A complex structure was apparent in the spectra for parallel configurations. We inferred that giant tunnel magnetoresistance observed in CoFeB/MgO/CoFeB junctions originates in coherent tunneling between the Δ_1 bands of crystallized CoFeB electrodes. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2173628]

I. INTRODUCTION

Tunnel magnetoresistance (TMR) effect in magnetic tunnel junctions (MTJs) has been studied extensively for the development of magnetic sensors and magnetoresistive random access memory (MRAM).[1,2] The TMR ratios of MTJs with an Al–O barrier have been improved over the last decade, but the TMR ratios have reached only about 70% at room temperature (RT).[3] On the other hand, theoretical calculations have predicted a giant TMR effect in single-crystal Fe(001)/MgO(001)/Fe(001) MTJs.[5,6] Yuasa *et al.* achieved a giant TMR ratio of 180% at RT in a single-crystal Fe(001)/MgO(001)/Fe(001) MTJ that was prepared using Molecular beam epitaxy (MBE) technique.[4] The giant TMR effect in such single-crystal MTJs is explained by coherent tunneling of Δ_1 electron states.

A giant TMR ratio of up to 200% at RT was also observed in MTJs with a highly oriented polycrystalline MgO(001) tunnel barrier and polycrystalline CoFe(001) or CoFeB electrodes.[7–9] Such excellent MTJs can be fabricated on a thermal oxidized Si substrate using sputtering technique and offer great advantages for industrial applications. However, the origin of giant TMR effects observed in CoFeB/MgO/CoFeB MTJs remains unclear.

We achieved a giant TMR ratio of up to 200% in CoFeB/MgO/CoFeB MTJs and measured d^2V/dI^2-V spectra to clarify the physical mechanism of the giant TMR. The d^2V/dI^2-V measurement is well known as a powerful technique to detect small changes of tunneling conductance (or resistance) that originate in inelastic tunneling and in characteristics of density of states (DOS) at the barrier/electrode interface.

II. EXPERIMENTAL PROCEDURE

Spin-valve-type MTJs of (Si/SiO_2)substrate/Ta(10)/PtMn(15)/$Co_{90}Fe_{10}$(2.5)/Ru(0.85)/$Co_{40}Fe_{40}B_{20}$(5)/MgO/$Co_{40}Fe_{40}B_{20}$(3)/Ta(10)/Ru(7)/NiFe(20)/Ta(5) (in nanometers) with MgO thicknesses (t_{MgO}) of 2.0–3.0 nm were prepared using a magnetron sputtering system (Magest S200, ULVAC, Inc.). The metal layers were deposited by dc sputtering at an Ar pressure of $(2.1–2.9)\times10^{-2}$ Pa and the MgO layer was deposited by rf sputtering at a pressure of 1.4×10^{-2} Pa. MTJs with areas of $3\times3–100\times100\ \mu m^2$ were fabricated using conventional photolithography and ion milling method and they were annealed at 350 °C for 1 h in a magnetic field of 4 kOe. The crystal structure at the MTJ interface was confirmed using cross-sectional transmission electron microscopy (TEM). The d^2V/dI^2-V measurements were performed at 6 K using a lock-in technique with a modulation amplitude of 1 mV. The bias direction was defined with respect to the top CoFeB electrode.

III. RESULTS AND DISCUSSION

Figure 1(a) shows typical TMR curves measured at RT and 6 K for CoFeB/MgO/CoFeB junction with t_{MgO} =2.5 nm. The MTJs showed giant TMR ratios of 192% at RT and 252% at 6 K, respectively. In our prepared MTJs, the TMR ratios were independent of t_{MgO} and the resistance-area

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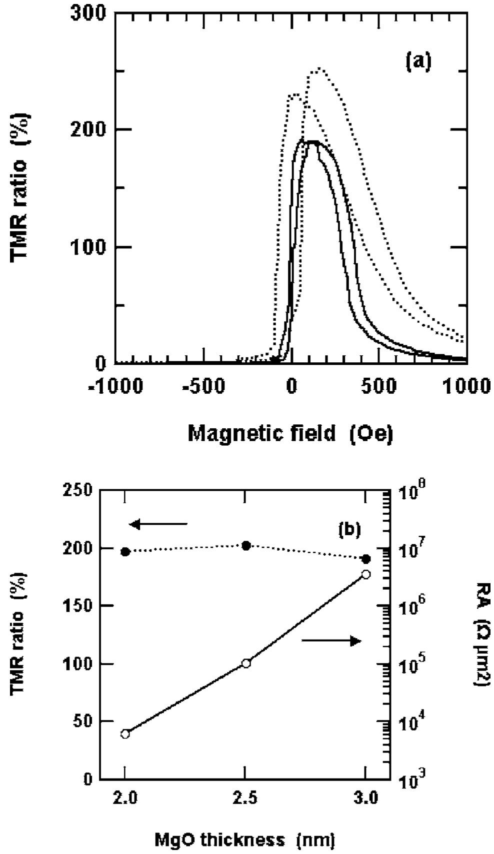

FIG. 1. (a) TMR curves of CoFeB/MgO/CoFeB MTJs at RT (solid line) and at 6 K (dotted line).(b) TMR ratio (solid circles) and *RA* (empty circles) of CoFeB/MgO/CoFeB MTJs at RT as a function of the MgO barrier thickness.

product (*RA*) increased exponentially with increasing t_{MgO} between t_{MgO}=2.0 and 3.0 nm, as shown in Fig. 1(b).

Figure 2(a) shows a cross-sectional TEM image for CoFeB/MgO/CoFeB MTJ with t_{MgO}=3.0 nm annealed at 325 °C for 5 h. We confirmed from the TEM image that each layer's morphology was smooth and that the interface between the CoFeB and MgO layers was particularly sharp. The enlarged TEM image is shown in Fig. 2(b). The MgO barrier layer had a crystalline structure with MgO(001) texture: other groups have reported similar results.[8,9] We found that both CoFeB electrodes were crystallized by annealing at high temperature, even though both CoFeB electrodes, as deposited, had amorphous structures.

Figure 3 shows the d^2V/dI^2-V spectra in the antiparallel (AP) magnetic configuration for various t_{MgO}. Sharp peaks at low bias voltages are attributable to magnon excitation. Along with these peaks, broad peaks were observed around ±600 mV for all t_{MgO}; the peak intensity is independent of t_{MgO}. Peaks at such high bias voltages were also observed in the d^2V/dI^2-V spectra for single-crystal Fe/MgO/Fe MTJs.[10] However, for single-crystal Fe/MgO/Fe MTJs, high-energy peaks appeared at higher voltages of ±1000 mV than those of CoFeB/MgO/CoFeB MTJs. The origins of the high-energy peaks in the Fe/MgO/Fe MTJs are explainable by taking into account the conduction channels between the majority and minority Δ_1 bands of Fe(001). The observed peak positions are consistent with the band edge of Δ_1 state

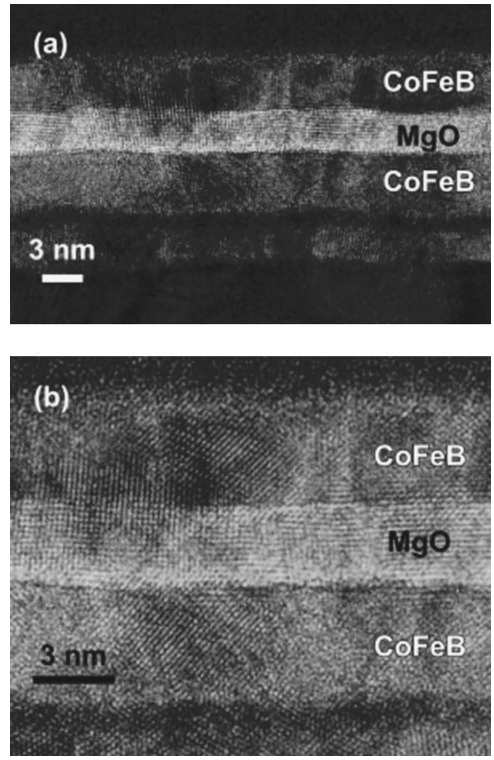

FIG. 2. (a) Cross-sectional TEM image of the CoFeB/MgO/CoFeB MTJs. (b) An enlarged cross-section TEM image of the MTJs shown in (a).

calculated for Fe(001). Although the band structure of crystallized CoFeB is not clear, we infer that the peaks around ±600 mV result from tunneling between the Δ_1 bands of CoFeB electrodes. The intensity of the high-energy peaks in Fe/MgO/Fe MTJs became prominent with increasing t_{MgO}. It is considered for MTJs with thin MgO that broad and small peaks are attributable to tunneling deviated from the barrier-normal direction. The probability of oblique tunnel-

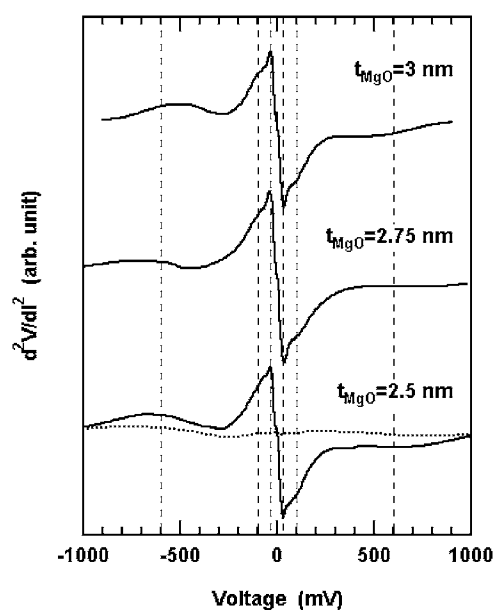

FIG. 3. The d^2V/dI^2-V spectra of the CoFeB/MgO/CoFeB MTJs at 6 K for the AP magnetic configuration (solid line). The spectrum in t_{MgO}=2.5 nm for the P configuration is shown as a dashed line for reference.

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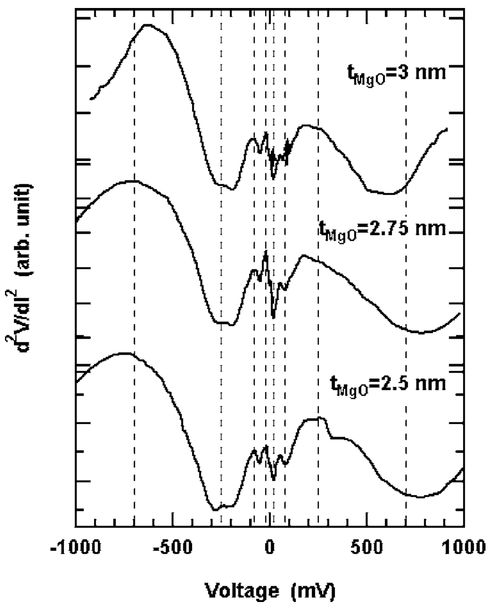

FIG. 4. The d^2V/dI^2-V spectra of the CoFeB/MgO/CoFeB MTJs at 6 K for the P magnetic configuration.

ing in CoFeB/MgO/CoFeB MTJs seems to be larger than that of single-crystal MTJs, even if the MgO barrier layer is thick, because the MgO layer is highly oriented, but it has a polycrystalline structure. For that reason, the high-energy peaks are considered small, even in CoFeB/MgO/CoFeB MTJs with a thick MgO barrier.

Figure 4 shows the d^2V/dI^2-V spectra in the parallel (P) magnetic configuration for various t_{MgO}. The spectral intensities of the P configuration were much lower than those of the AP configuration. The vertical axis scale is enlarged to afford a better view of the detailed structure. The intensities of peaks around ±30 mV attributed to magnon excitation for the P configuration were much lower than that for the AP configuration, indicating that the spin-flip inelastic excitation is dominant for AP. The spectra for the P configuration have a complex structure with several peaks around ±100, ±250, and ±700 mV and the peak positions are independent of t_{MgO}, as shown in the single-crystal Fe/MgO/Fe MTJs.[10] The peak positions are slightly lower and the second peaks at ±250 mV are smaller than those of the Fe/MgO/Fe MTJs. The origin of the complex spectra for the P configuration and differences of the spectra between CoFeB/MgO/CoFeB and Fe/MgO/Fe MTJs are not clear at present, but we infer that these spectra for the P configuration contain information related to the particular tunneling process through the highly oriented MgO barrier.

IV. SUMMARY

The d^2V/dI^2-V spectra were measured to investigate the tunneling mechanism in CoFeB/MgO/CoFeB MTJs, which exhibited the giant TMR effect of up to 200%. The shapes of the d^2V/dI^2-V spectra for the CoFeB/MgO/CoFeB junctions are similar to those of the single-crystal Fe(001)/MgO(001)/Fe(001) junctions. We observed sharp peaks that were attributed to magnon excitation at low bias voltages and broad peaks around ±600 mV for AP magnetic configuration. In the spectra for the P magnetic configuration, small peaks attributed to magnon excitation and the complex structure were observed. We inferred that the broad peaks around ±600 mV for the AP magnetic configuration result from coherent tunneling between the Δ_1 bands of CoFeB electrodes and that coherent tunneling is the origin of the giant TMR effect in the CoFeB/MgO/CoFeB system.

ACKNOWLEDGMENTS

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